SPECIFICATION OF PRECIPITATION FROM THE 700-MILLIBAR CIRCULATION

WILLIAM H. KLEIN

Extended Forecast Branch, National Meteorological Center, U.S. Weather Bureau, Suitland, Md.[1]

[Manuscript received July 1, 1963; revised July 22, 1963]

ABSTRACT

Five-day precipitation amounts observed during 10 recent winters in 40 equal-area circles covering the United States are assigned a numerical index according to the proportion of light, moderate, or heavy precipitation falling within each circle. The synoptic climatology of precipitation is investigated through construction of correlation fields between this index and the simultaneous 5-day mean 700-mb. height departure from normal in North America and adjacent ocean areas. On the basis of the analogy between lines of equal correlation and lines of equal height anomaly, inferences are drawn concerning the association between precipitation and other meteorological factors. Schematic models are then constructed showing preferred portions of the long-wave pattern for heavy and light precipitation in different parts of the nation.

By use of a screening program on the IBM 7090, the field of 700-mb. height is found to be more effective than that of either sea level pressure or 700–1000-mb. thickness in specifying 5-day precipitation. On the average, almost 40 percent of the variance of precipitation can be explained by 2 to 6 heights, but the specification is more accurate in the West and South than in the East or North. Multiple regression equations are derived for each reference circle and found to hold up well on 4 years of independent data.

1. INTRODUCTION AND HISTORY

The late Dr. Harry Wexler was one of the first meteorologists to relate large-scale precipitation regimes to the upper-air circulation. In 1938, he and Namias [24] found that abnormalities of summer rainfall were closely aligned with moist and dry tongues on monthly mean isentropic charts. In subsequent work, 5-day precipitation patterns were associated directly with various features of the planetary wave train at the 700-mb. level by Smith [21] in 1942, Klein [7] in 1948, and Martin and Hawkins [15] in 1950.

An important advance in this field was made by Stidd [22] in 1954, who showed how correlation fields could be interpreted to clarify the relation between precipitation and circulation. The term "specification" was introduced in 1956 by Malone and colleagues [14], who employed Chebyschev polynomials to characterize the 700-mb. circulation and multiple regression equations to translate this circulation into concomitant weather elements; i.e., to specify the weather from the concurrent circulation pattern.

The present paper is an outgrowth and extension of these earlier studies. After presentation of the basic data (section 2), the relation between 5-day precipitation and the simultaneous mean 700-mb. circulation is studied by the correlation field technique (section 3) in order to throw light on the synoptic climatology of rainfall and derive schematic models for precipitation in relation to the long-wave pattern. In section 4 an objective method of specifying 5-day precipitation amounts from concurrent 5-day mean 700-mb. heights is derived by use of a stepwise method of multiple regression called screening which was introduced to meteorology by Miller [18] and successfully applied to prediction of 5-day mean temperatures by Klein, Lewis, and Enger [10]. The results of tests on independent data are discussed in section 5.

2. BASIC DATA

Since precipitation is highly localized and discontinuous in nature, several smoothing devices were employed. In the first place, 5-day mean rather than daily data were used. Secondly, total precipitation amounts were divided into light, moderate, or heavy classes. These classes are routinely used in extended forecasting [19] and are defined from 36 years of climatological records, so that each class normally occurs one-third of the time [1]. In arid regions "no precipitation" may be used in place of "light" and "precipitation" in place of "heavy."

The third smoothing device was a form of areal-averaging illustrated in figure 1. The lines divide the United States into 40 regions considered to be roughly homogeneous on the basis of topography, drainage basins, Weather Bureau forecast districts, and normal precipitation amounts. For example, the north-south lines on either end represent the Appalachian and the Cascade–Sierra Nevada ranges, while the Continental Divide is delineated by the 3d line from the left. Equal-area, non-

[1] A preliminary version of this paper was presented at the 43d Annual Meeting of the American Meteorological Society in New York City, January 21, 1963.

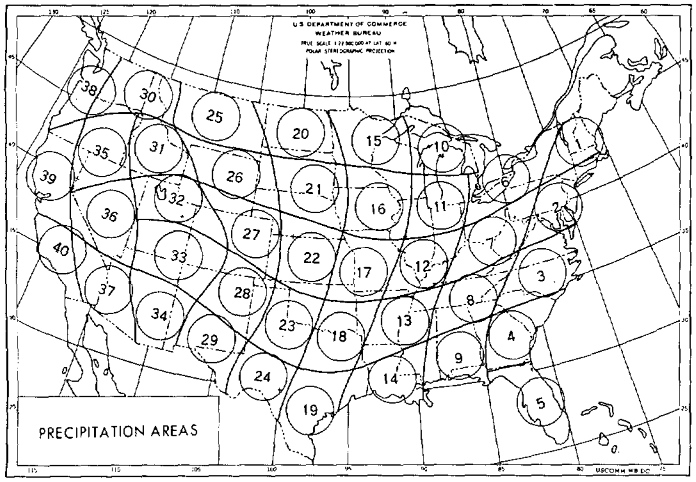

FIGURE 1.—Grid of 40 equal-area circles at which the precipitation index was measured. Each circle is located near the center of climatologically homogeneous areas delineated by the solid lines.

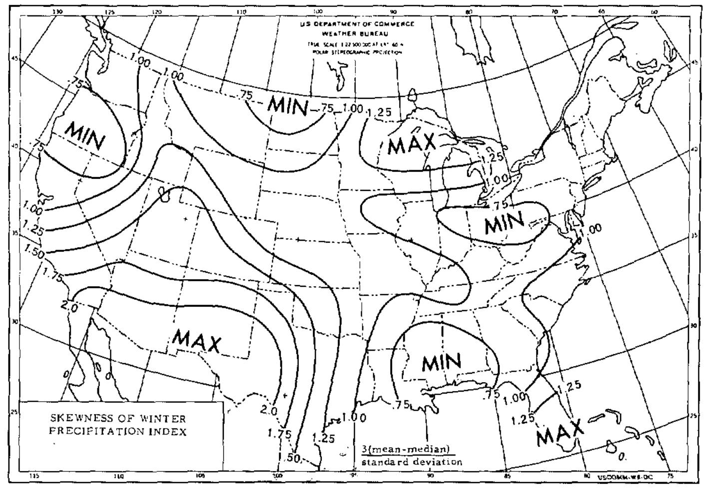

FIGURE 3.—Skewness of the precipitation index computed from the formula: 3 (mean−median)/standard deviation. Highest and lowest values are indicated by MAX and MIN respectively. The data are based on 140 5-day periods during the winter months from December 1949 to March 1959.

Category	Dominant class	Remaining class	Example
1	L	0	L
2	L	M or H	L M
3	M	0 or mostly L	M L
4	M	mostly H	M H
5	H	M or L	H M
6	H	0	H

FIGURE 2.—Definition of the precipitation index where symbols mean the following: L—light, M—moderate, H—heavy, 0—none, dominant—more than half.

overlapping circles, about 230 mi. in diameter, were placed approximately in the center of each area. The observed 5-day precipitation within each circle was then tabulated from maps analyzed in terms of 5-day precipitation classes. Such maps have been prepared routinely in the Extended Forecast Branch for the past 20 years on the basis of reports at several hundred stations in the United States.

With the aid of a numerical index illustrated in figure 2, each case was placed in one of six categories which express the proportion of light, moderate, or heavy precipitation falling within each circle. In dry regions no precipitation was considered as light, and precipitation as heavy. The two extreme categories are 1 and 6, for which all portions of the circle must be analyzed as light or heavy respectively. For categories 2 and 5 more than half, but not all, of the circle must be analyzed as light or heavy, respectively, regardless of the rest of the circle. The remaining two classes are both predominantly moderate, with category 3 on the light, and category 4 on the heavy, side.

The resulting precipitation index was tabulated for 140 non-overlapping 5-day periods, one during each week of 10 winters from December 15, 1949 to March 15, 1959. When totaled over all 40 areas, there were approximately an equal number of cases in the first five categories, but decidedly fewer in category 6. As a result, the skewness or asymmetry was positive over the entire country, as illustrated in figure 3. Here the skewness was calculated from the formula [20]:

$$3\ (\text{mean}-\text{median})/\text{standard deviation}$$

Maximum positive values (over 2) are found in the arid Southwest where some circles had over half their cases in category 1. Despite this skewness, correlations of precipitation index against 700-mb. height were computed, since it has been shown that deviations from the normal distribution do not produce serious errors in a correlation study [16].

Figure 4 shows the grid of points at which 700-mb. height [2] was taken. A network of 70 points was used, 10° apart, extending from 30° to 70° N. and from 50° to 180° W., the same grid used in an earlier study of temperature [10]. Maps were constructed showing the field of simple linear correlation coefficient between the precipi-

[2] Henceforth the word "height" will usually apply to the anomaly, or departure from local normal, rather than to absolute value, where the normal is given in [23]. Likewise the word "flow" will generally refer to the anomalous, rather than the absolute, geostrophic wind components.

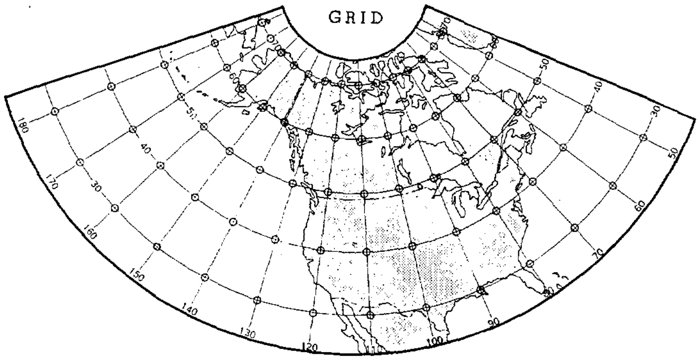

FIGURE 4.—Network of 70 grid points used to delineate the 700-mb. height field. Heights were taken at standard intersections of latitude and longitude, 10° apart, marked by open circles.

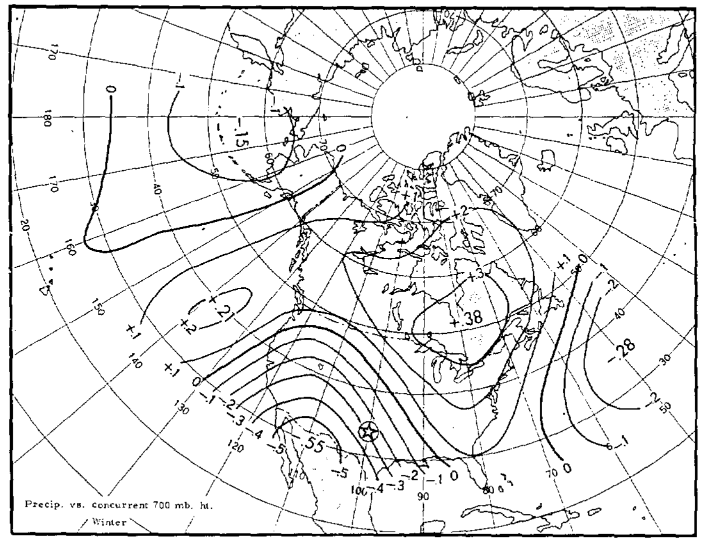

FIGURE 5.—Analysis of the simple linear correlation coefficients between the precipitation index in circle number 23 (located by star) and simultaneous 5-day mean 700-mb. height anomaly at grid of points shown in figure 4 for 140 winter cases.

tation index in each of the 40 circles and the simultaneous 5-day mean 700-mb. height departure from normal at each of the 70 grid points. The resulting correlation fields are illustrated in figures 5 and 7 where the individual correlation coefficients have not been plotted at each grid point, but the analysis based upon them is given by the isopleths of equal correlation.

3. SYNOPTIC CLIMATOLOGY

Figure 5 indicates that winter precipitation in the Panhandle area of Texas is most closely related to 700-mb. height in northern Mexico. The magnitude of the correlation is 0.55 and the sign is negative, thereby showing that below normal heights in Mexico are associated with heavy precipitation in northern Texas, while above normal heights accompany dry weather. Another important correlation center is located over James Bay, where a positive correlation of 0.38 indicates that positive height anomalies there are accompanied by heavy rain in the Panhandle, while negative anomalies go with light.

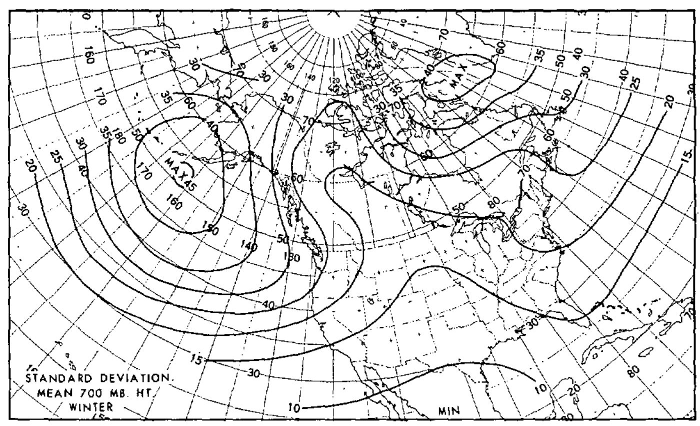

FIGURE 6.—Standard deviation of 5-day mean 700-mb. height anomaly in tens of feet for 140 winter cases. Highest and lowest values are indicated by MAX and MIN.

Figure 6 presents the standard deviation of 5-day mean 700-mb. heights used in the present paper. It reveals the characteristic minimum over central North America, flanked by maxima over the adjacent oceans, which was noted in an earlier study of daily values [8]. Over most of the United States gradients are very weak, so that it seems permissible to disregard the spatial variation of the standard deviation of 700-mb. height. With this assumption, Stidd [22] demonstrated that correlation fields may be interpreted in a qualitative sense as if they represent the anomalous component of the 700-mb. geostrophic flow. The latter, in turn, has been shown to reflect the actual wind flow at a lower level [6].

Thus the tight gradient of isopleths over the Texas Panhandle in figure 5 indicates that strong southeasterly flow (with respect to normal) produces heavy precipitation, while northwesterly flow brings dry weather. From this figure we may draw other interesting inferences about the synoptic climatology of rainfall in the Panhandle such as: (a) the origin of the anomalous flow producing heavy precipitation, the Gulf of Mexico; (b) the curvature of this flow, approximately straight; (c) the correlation between local height and precipitation, −0.28; and (d) the distance along a latitude circle to the axis of negative correlation, 570 mi.

Similar reasoning has been applied to maps showing the correlation between the field of 700-mb. height anomaly and the precipitation index in each of the other 39 circles. Examples of quite different types of precipitation regimes illustrated by these correlation fields are given in figure 7 where the following features are suggested for wet weather (and the reverse for dry): (a) in New England—southeasterly flow from the Atlantic; (b) in the Gulf States—southerly flow from the Gulf of Mexico; (c) in Montana—a local center of negative height anomaly with a positive center over Alaska; (d) in California—southwesterly flow

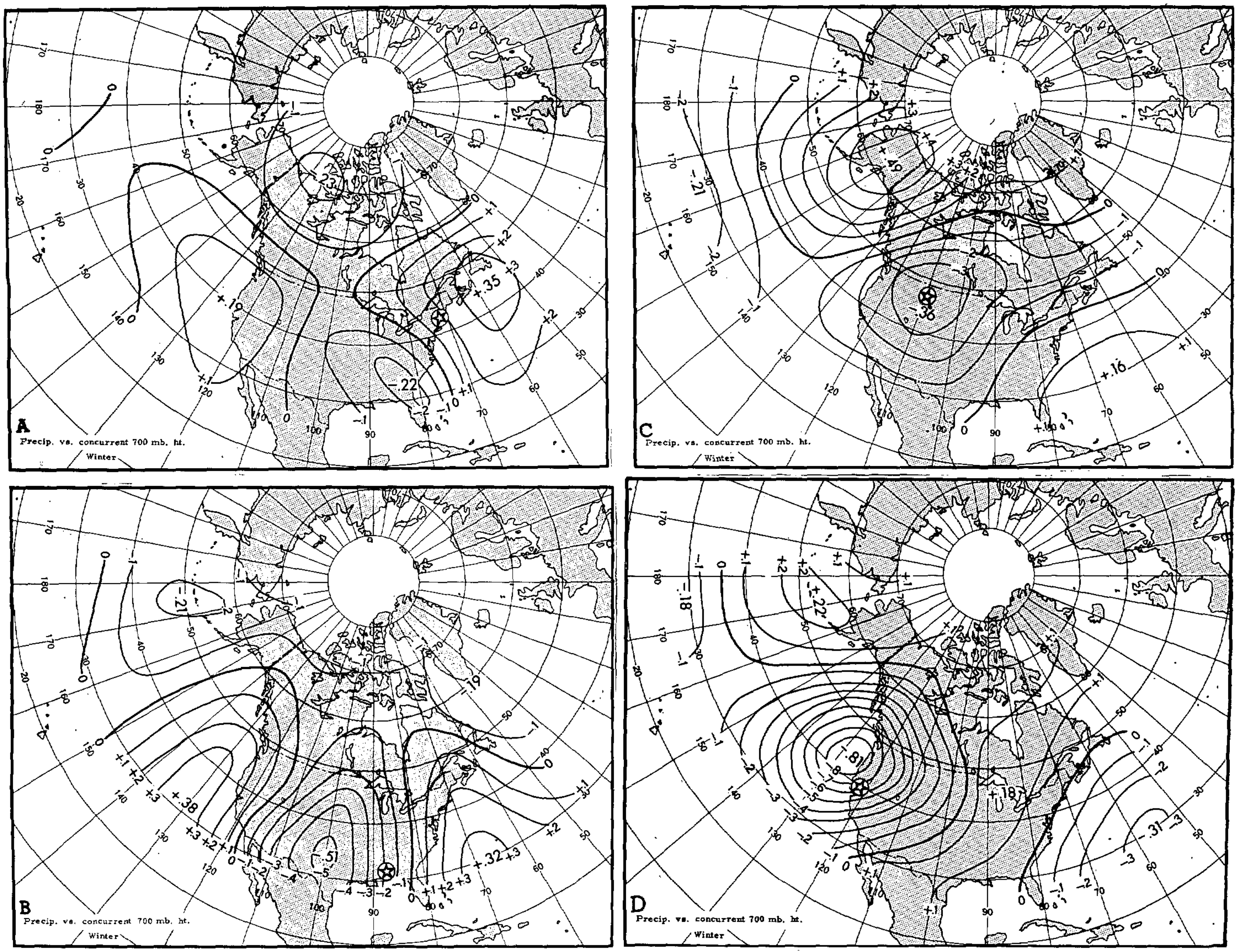

FIGURE 7.—Correlation fields between the 5-day mean 700-mb. height anomaly at grid of points shown in figure 4 and the concurrent precipitation index in the following circles (located by stars): (A) 1; (B) 9; (C) 25; (D) 39. All data for 140 winter cases.

from the Pacific and below normal heights locally. Similar features were noted by Stidd [22] working with different time and space scales (monthly means and State-wide averages), a different period of record (1939–52), and different data treatment (cube roots of precipitation).

In order to summarize the information contained in all 40 correlation maps, figures 8 to 14 have been prepared. Figure 8 shows the local components of anomalous 700-mb. flow indicated by the correlation fields to be conducive to heavy precipitation in different parts of the country. Southeasterly components are favorable, not only in the Panhandle (fig. 5) and New England (fig. 7A), but also in most of the Great Plains and along the Atlantic Coast. The preferred direction of anomalous flow is southerly in the remainder of the eastern half of the nation (fig. 7B) (in general agreement with earlier findings of Miller [17] and Klein [7]), easterly just east of the Continental Divide, and southwesterly in most of the Far West (fig. 7D).

Figure 9 gives the moisture source where the correlation fields suggest that the anomalous 700-mb. flow originates for heavy precipitation. This was obtained by following the correlation isopleth (assumed to represent the air trajectory) from the reference circle upstream to its first intersection with a large body of water. As illustrated in figures 5 and 7, primary sources are the Gulf of Mexico for most of the South and Mid-West, the Pacific for the west coast, and the Atlantic for the east coast [22]. In the blank area on either side of the Rockies, the anomalous flow does not seem to originate in any well defined source of moisture.

Figure 10 shows the local curvature of the anomalous 700-mb. flow conducive to heavy precipitation. As expected, it is cyclonic for most of the country [21], but straight or even anticyclonic curvature favors heavy rain in a belt extending from Oklahoma through the Ohio and Tennessee Valleys into the Northeast [7].

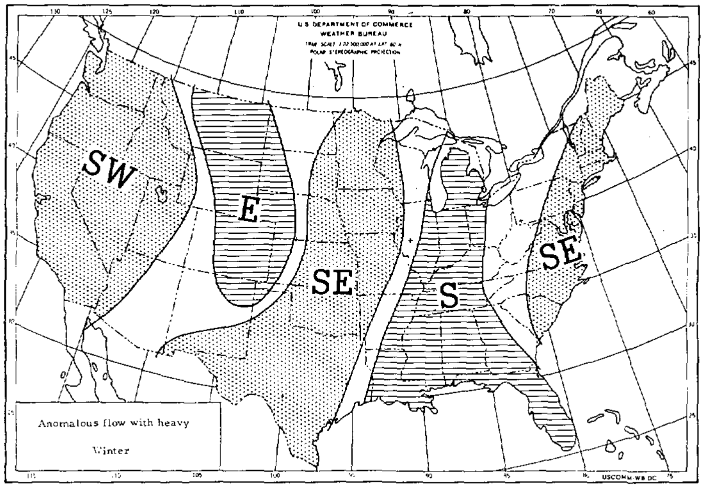

FIGURE 8.—Local component of anomalous 700-mb. flow conducive to heavy precipitation in winter with symbols as follows: E—easterly, SE—southeasterly, S—southerly, SW—southwesterly. In unshaded areas no single wind direction predominates.

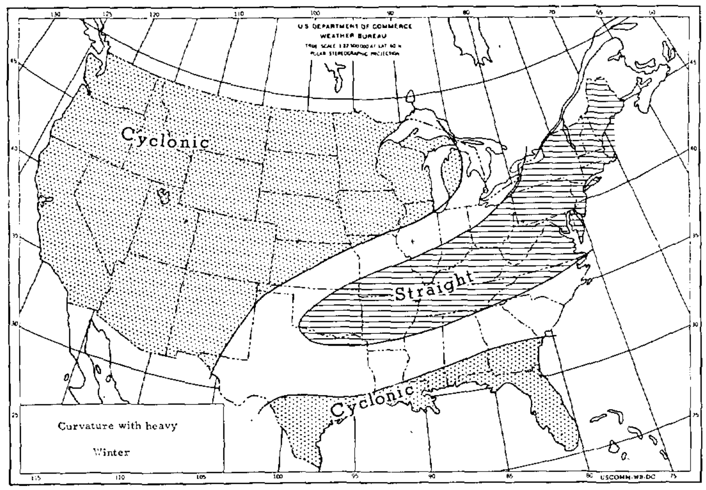

FIGURE 10.—Local curvature of anomalous 700-mb. flow conducive to heavy precipitation in winter. Heavy precipitation is characterized by cyclonic curvature in most of the country (stippled), by straight flow in a band from Oklahoma to New England (hatched), and by no predominant curvature in the unmarked area.

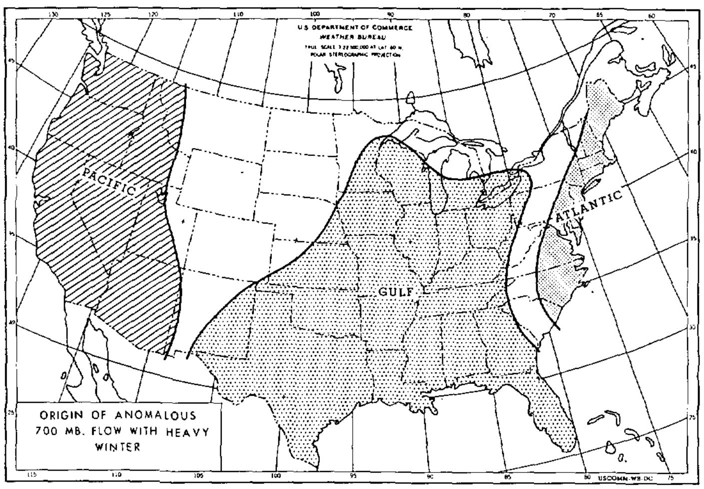

FIGURE 9.—The body of water where the anomalous flow at 700 mb favorable to heavy precipitation originated for 140 winter cases In blank areas no single source of moisture predominated.

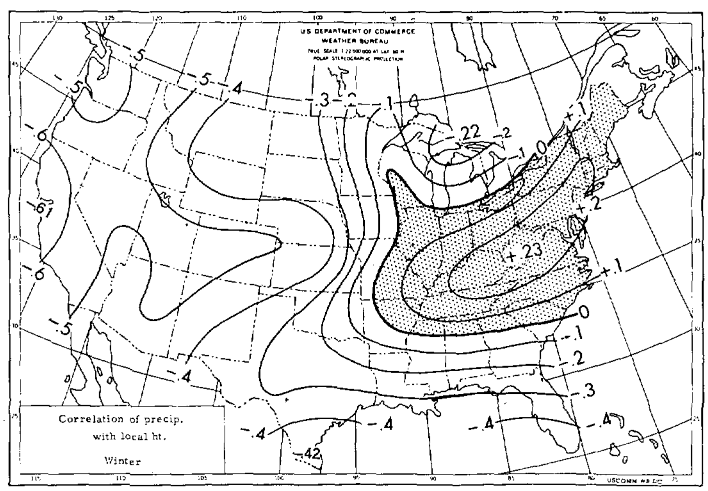

FIGURE 11.—Analysis of simple linear correlation coefficients between the precipitation index in each circle and the simultaneous local 5-day mean 700-mb. height anomaly for 140 winter cases. Area of positive correlation is shaded.

Figure 11 reveals similar information in the form of the correlation coefficient between the precipitation index and the 700-mb. height anomaly directly overhead. In most of the nation heavy rains are accompanied by below normal heights, and dry weather by above normal heights, as indicated by negative correlations which reach a maximum of −0.61 on the west coast. On the other hand, the correlations are positive over much of the East and Mid-West (shaded) with maximum value of 0.23 over West Virginia, thereby indicating a slight tendency for heavy rain to go with high heights and light rain with low heights.

In all cases, precipitation is directly related to a center of negative correlation near or west of the reference circle. Figure 12 shows that the magnitude of this negative correlation varies from 0.22 in New England (fig. 7A) to 0.81 in northern California (fig. 7D). The length of the arrows represents the distance to the center of correlation and is much greater in the eastern than in the western half of the Nation.

This information is given in greater detail in figure 13, which shows the zonal distance in miles from the precipitation circle to the axis or trough of negative correlation. The maximum distance, almost 1,400 mi., is found over the Middle Atlantic States. The minimum distance is found over the Rocky Mountain States (fig. 7C), and in the shaded area, near Wyoming, the center of negative correlation is actually slightly east of the circle.

The preceding material can be summarized in a qualitative sense if, in addition to the assumption made pre-

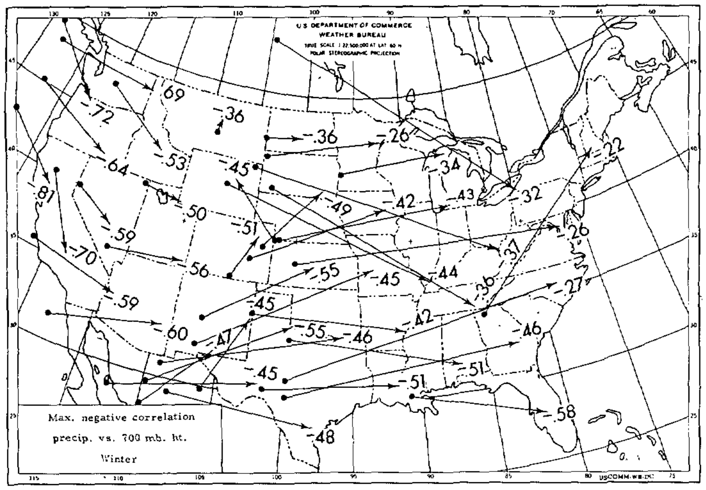

FIGURE 12.—Maximum negative correlation between the precipitation index in each circle and the simultaneous 5-day mean 700-mb. height anomaly for 140 winter cases. The point of highest correlation is shown as a heavy solid dot, the center of the reference circle is located at the tip of the arrow, and the value of the correlation coefficient is written next to each circle.

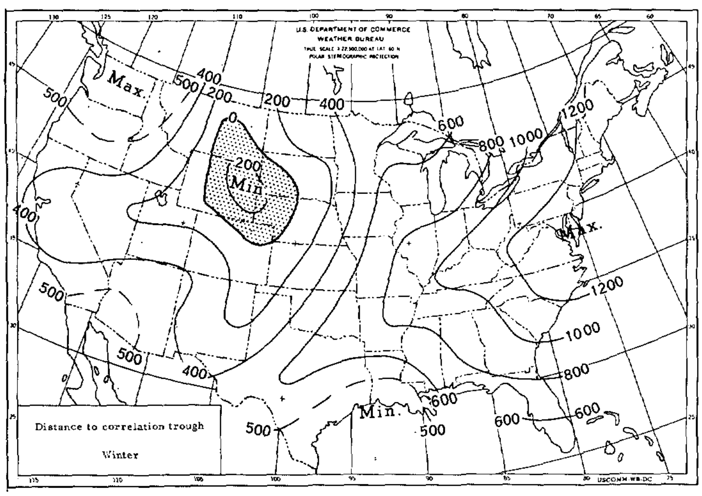

FIGURE 13.—Zonal distance in miles to the nearest axis of negative correlation between the precipitation index in each circle and the simultaneous 5-day mean 700-mb. height anomaly for 140 winter cases. Distances are considered positive when the correlation trough is west of the circle, negative when it is to the east (stippled).

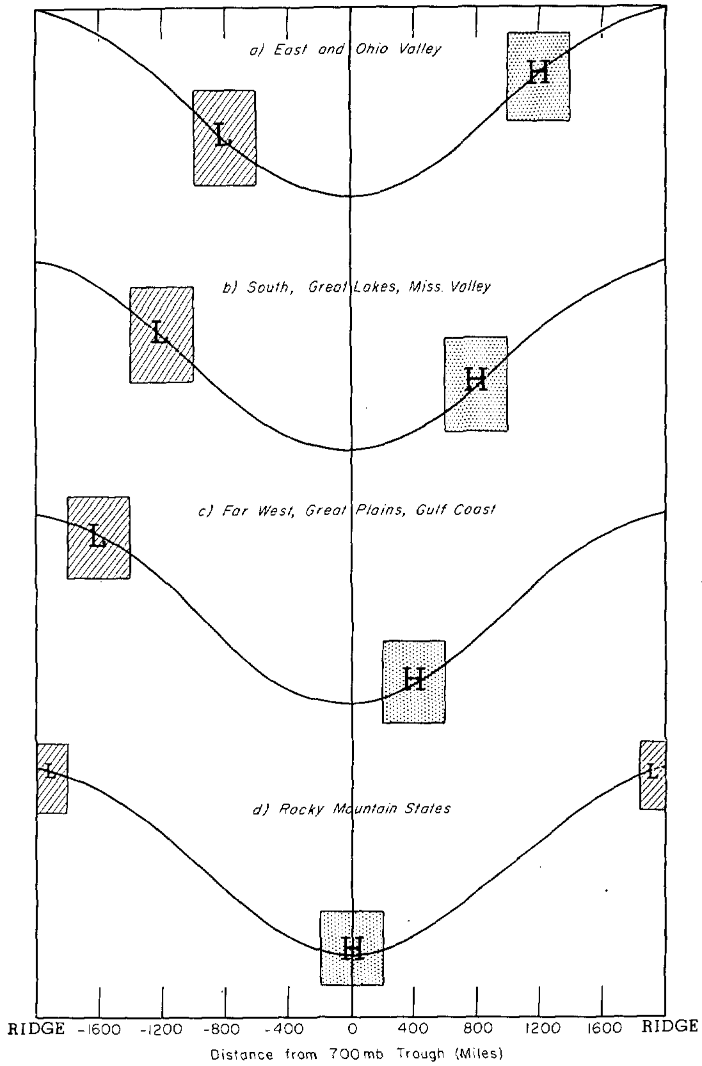

FIGURE 14.—Optimum regions for heavy and light precipitation in winter in different parts of the United States relative to a sinusoidal 700-mb. contour. Distance from the 700-mb. trough given along the abscissa is assumed to be 2000 mi. to the ridges up- and down-stream, with positive values when the trough is west of the reference area and negative values when the trough is east of the area.

viously about the analogy between anomalous flow and correlation fields [22], we also assume that the contours on a normal 700-mb. map [23] run directly from west to east, so that troughs and ridges are negligible in amplitude on normal charts compared to 5-day mean charts. We can then construct the schematic models for winter precipitation shown in figure 14, where the sinusoidal curves represent contours, which reach their minimum latitude at the trough line (shown in center at 0). The ridge lines on either end are drawn 2,000 mi. away from the trough on the basis of previous studies of average wavelength on 5-day mean maps [2]. The squares marked H and L represent optimum portions of the wave train for heavy and light precipitation in different parts of the country.

In most of the eastern half of the Nation heavy precipitation is likely to occur in southwesterly flow about half way between trough and ridge, and conversely for light, in agreement with the author's earlier model for the Tennessee Valley [7]. This optimum area for heavy rainfall is closer to the ridge in the East and Ohio Valley (a), and closer to the trough in the South and Mid-West (b). On the other hand, in the western half of the Nation (and also along the immediate Gulf Coast), the optimum region for heavy is much closer to the trough than to the ridge. This is illustrated in curve (c) for the Far West, Great Plains, and Gulf Coast, where heavy precipitation occurs only 400 mi. east of the trough in pronounced cyclonic flow, light about 400 mi. east of the ridge in pronounced anticyclonic curvature. The extreme condition is found over the Rocky Mountain States (d), where only location directly under the trough or ridge, and not meridional wind component, appears to be critical.

It is noteworthy that the models of figure 14 resemble composite 700-mb. maps for heavy and light 5-day precipitation presented by Martin and Hawkins [15] for different parts of the country. They are also in good agreement with synoptic experience and should be generally applicable to daily, as well as 5-day, precipitation.

4. SPECIFICATION EQUATIONS

In order to develop quantitative specification equations, a stepwise method of multiple regression called screening [18] was applied, using a program written by Lewis [11] for the IBM 7090 computer. This program selects first the height giving the correlation of greatest absolute magnitude with precipitation; second the height giving the highest partial correlation with precipitation, holding the first selected height constant; third the height giving the highest partial correlation after removal of the effect of the first two points picked, etc. The termination point for this procedure is not rigorously defined, but is based upon a combination of synoptic reasoning and levels of significance given by the F test as applied to the percent of explained variance added by each successive predictor [10].

A typical equation resulting from this screening procedure is illustrated in figure 15. This is for the precipitation index in circle number 23, in the Panhandle, the same area whose correlation field was presented earlier (fig. 5). The most important single predictor of precipitation in this circle is 700-mb. height at the intersection of 30° N., 110° W., and the correlation between the two variables is −0.54. The height which contributes the most additional information is located at 40° N., 100° W. Combination of this height with the one at 30° N., 110° W. yields a multiple correlation of 0.63.

Combination of the first two heights with any additional one produces best results when the height at 50° N., 70° W., near the center of maximum positive on the original correlation field (fig. 5), is used, raising the multiple correlation to 0.67. Since no additional height was able to increase the explained variance by more than 2 percent, the screening process was stopped at this point. The final specification equation is written at the top of figure 15. If we disregard the constant term, the negative sign of the first regression coefficient and the positive sign of the last two indicate that southeasterly flow produced by low heights at 30° N., 110° W., and high heights at the other two points favors heavy precipitation, and conversely northwesterly flow favors dry weather.

Similar multiple regression equations were derived separately for each of the 40 circles. In almost half of the cases (18 circles) exactly 3 heights were selected, as in the situation illustrated in figure 15. In the remaining circles 2, 4, or 5 heights were used, except for three areas in which as many as 6 heights were picked. On the average 38.4 percent of the variance of precipitation was explained by 3.6 heights, but there was considerable geographical variation as illustrated by figure 16. In the shaded areas of the West and South, better than 40 percent of the variance was explained, with maximum values over 70 percent along the west coast. On the other hand, in the unshaded areas of the East and North the specification

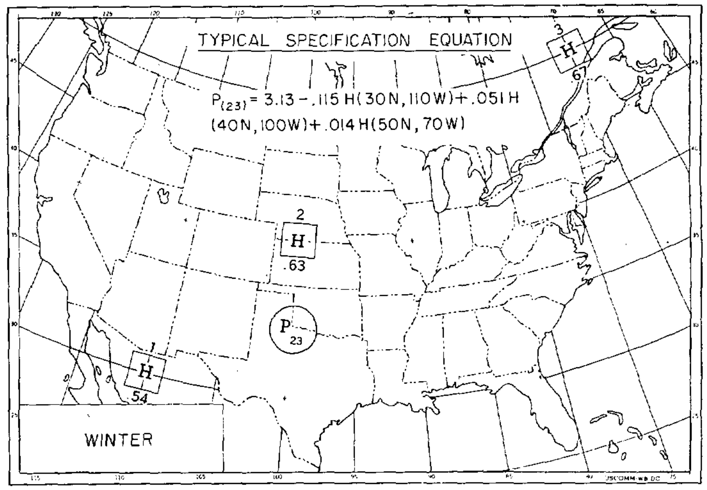

FIGURE 15.—Multiple regression equation used in specifying the precipitation index in circle number 23 (located by circle) during the winter season as a function of the simultaneous 5-day mean 700-mb. height anomaly (in tens of feet) at indicated points. The location of the height is given by the open square, and the multiple correlation coefficient after inclusion of the given height by the decimal below.

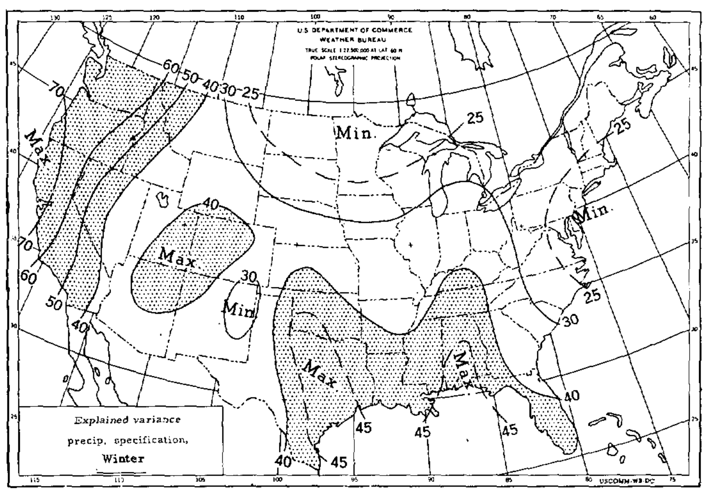

FIGURE 16.—Percent of variance of the precipitation index explained by specification equations of the type shown in figure 15. From 2 to 6 heights were selected for each circle by the screening techniques. Analysis is based upon values at 40 circles on dependent sample of 140 winter cases from December 1949 to March 1959.

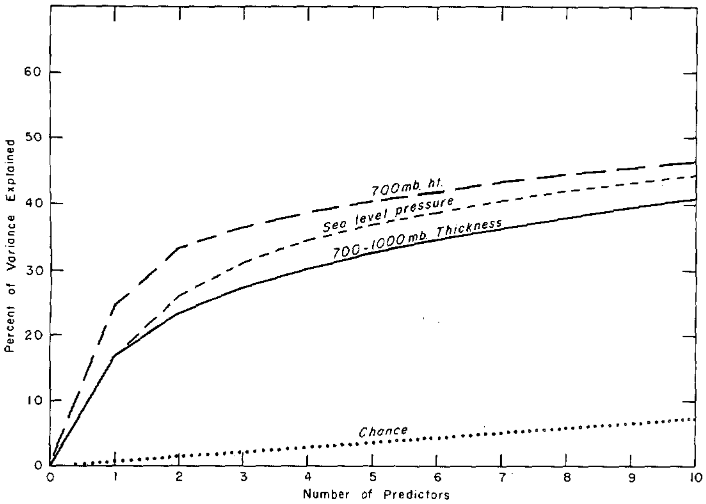

FIGURE 17.—Percent of variance of the precipitation index explained by multiple regression equations containing the number of variables given along the abscissa. The results are averages over all 40 reference circles and are given separately for simultaneous 5-day mean anomalies of 700-mb. height, sea level pressure, and 700–1000-mb. thickness. The dotted line gives the values expected by chance. Data based on dependent sample of 140 winter cases.

was much poorer, with minimum values under 25 percent along the Middle Atlantic Coast and over the Upper Mississippi Valley.

The relation between precipitation and simultaneous values of other circulation parameters has also been investigated by use of the screening program. Figure 17 summarizes the results obtained from anomalies of 5-day mean sea level pressure and 700–1000-mb. thickness, measured at the same grid of points shown earlier for 700-mb. height (fig. 4). The results were averaged over all 40 circles and are shown separately for thickness, sea level pressure, and 700-mb. height. The dotted line gives the results that would be expected by chance if the variables had been selected at random.[3] Although all three circulation parameters exhibit results well beyond chance, most of the superiority comes from the first few predictors. The additional variance explained by adding predictors after the fifth is hardly greater than the chance expectation, in spite of the fact that the predictors were not drawn at random.

Perhaps the most important conclusion to be drawn from this figure is the fact that, despite regional differences, on the average neither pressure nor thickness explains as much of the variance of precipitation as does 700-mb. height. A similar conclusion was reached by Friedman [3] in a study of daily precipitation. For this reason, and also because it has long been the basic chart in extended forecasting [19], the 700-mb. map has been selected for specifying precipitation on a routine basis from equations of the type illustrated in figure 15.

5. TESTS ON INDEPENDENT DATA

In order to investigate the stability of the specification equations derived in the preceding section, they were tested during the four winters (December 1959 through March 1963) immediately following the 10 winters of the original sample (December 1949–March 1959). As before, overlap of the 5-day periods was eliminated by selecting cases a week apart, but the winter period was defined as December 1–March 31 instead of December 15–March 15 as previously. A total of 68 cases was thus available during the test period, compared to 140 for the original sample. For each of these cases the precipitation index observed within each of the 40 circles was obtained from maps analyzed in terms of 5-day precipitation classes by the same procedure followed previously (section 2). These observed values of the precipitation index were then compared to values computed by applying the specification equations to 5-day mean 700-mb. height departures from normal observed during each of the 68 test periods.

The specifications at each circle were verified in terms of the reduction of error [13]:

$$RE=1-\frac{\sum_{i=1}^{68}(O_i-S_i)^2}{\sum_{i=1}^{68}(\bar{O}-O_i)^2}$$

where O_i is the observed, S_i the specified, and $\bar{O}$ the mean precipitation index computed from the 10-year dependent sample.

Values of RE were computed separately for each circle, plotted, and analyzed, with results shown in figure 18. There is considerable similarity between the large-scale features of this map and those of figure 16, the comparable quantity for the dependent sample, with maximum values in western and southern areas, and minimum values in northern and eastern sectors. The average RE for all 40 circles was 34.8 percent, compared to 38.4 percent on the dependent sample (section 4). Thus it may be concluded that the specification equations are very stable and hold up well on new data.

The objective specifications of precipitation index were also verified in terms of 5-day precipitation classes. In order to avoid the tendency of regression equations to "hedge" by not forecasting the extremes as often as they are observed, a set of class limits was derived for each circle and each month by applying the specification equations to the 5-day mean 700-mb. heights observed during the 140 original periods. The resulting specifications were then ranked and divided into either equal thirds (in areas of light, moderate, or heavy) or fractions dependent on the normal frequency of occurrence of no precipitation within each circle [1]. For example, in

[3] The chance line in figure 17 was computed from the following formula derived by Gilman [4] from equations of Lorenz [13]: $EV=n/(M-1)$, where EV is the explained variance, n is the number of predictors, and M is the number of cases. An equation which gives a slightly higher expected value was used by Lintner [12]: $EV=(n+1)/M$.

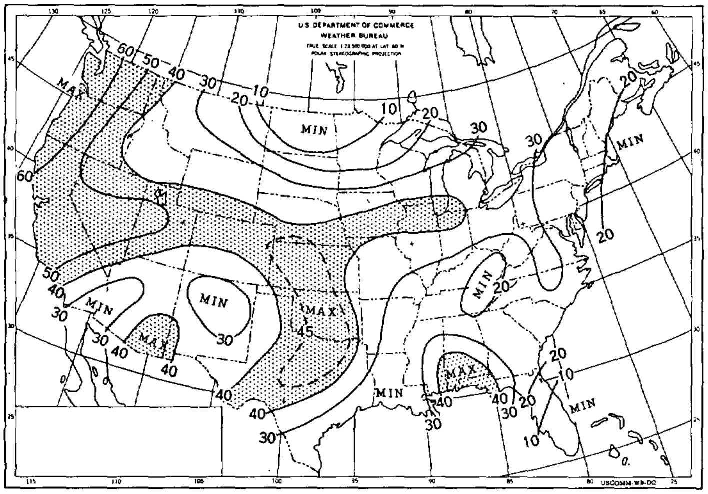

Figure 18.—Geographical distribution of the reduction of error obtained by specifying the precipitation index from observed 5-day mean 700-mb. heights for the independent sample of 68 cases from December 1959 to March 1963.

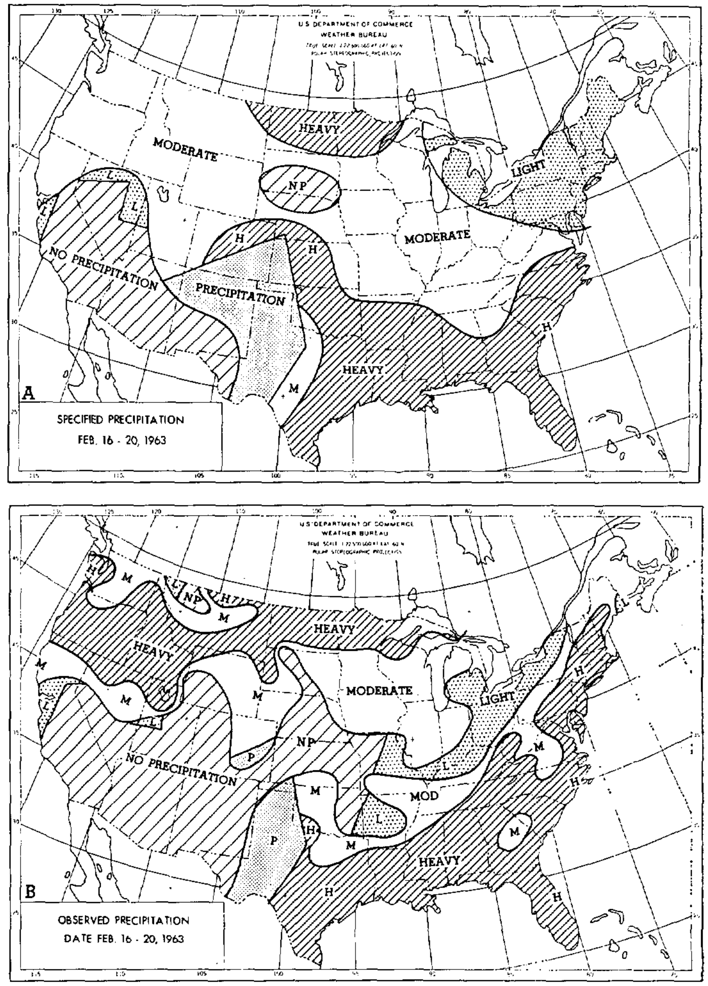

Figure 19.—Specified and observed 5-day precipitation amounts for the period February 16–20, 1963. Analysis is in terms of the five classes customarily used in the U.S. Weather Bureau; heavy (H), moderate (M), light (L), precipitation (P), and no precipitation (NP). (A) is the objective estimate obtained from the observed 5-day mean 700-mb. heights; (B) is the verifying map. The skill score was 31.6.

circle number 39 in December, a specified precipitation index of 4.3 or greater is considered in the heavy class (occurring ⅓ of the time); 3.1 to 4.3, moderate (17 percent frequency); and 3.0 or lower, no precipitation (49 percent frequency).

The class limits thus established on the dependent sample were assumed to apply to the independent data and were used to convert the precipitation specified at each circle into the appropriate 5-day precipitation class. After the specified class for each circle was plotted on a map, lines were drawn by interpolation delineating the distribution of precipitation classes over the entire country. A typical case is illustrated in figure 19. These maps were then verified in the manner customarily used in extended forecasting [19]; i.e. in terms of the skill score [20] computed at a grid of 100 cities fairly evenly spaced over the United States. The average skill score for all 68 cases was 28.9. This figure compares favorably with an average skill score of 27.4 obtained in an earlier experiment [5] in which four experienced forecasters specified 5-day precipitation from observed 5-day mean 700-mb. maps during 40 winter cases chosen at random between 1948 and 1957. The specification equations were recently applied to these 40 cases and yielded an average skill score of 28.1. It therefore appears that the multiple regression equations derived in this paper can produce in a few minutes objective specifications of 5-day precipitation which are at least as good as those prepared subjectively by skilled synoptic meteorologists.

6. CONCLUDING REMARKS

Up to this point only observed 700-mb. heights (i.e., perfect forecasts) have been discussed. To be useful under operating conditions, the specifications equations must be applied to prognostic 5-day mean 700-mb. charts. This was done on a routine basis 3 times a week in the Extended Forecast Branch during a 5-month period from November 1962 to March 1963. The resulting objective precipitation forecasts for all 63 cases in this sample had an average skill score of only 9.5, disappointingly low compared to the score of 29 obtained by specification from observed heights (section 5). Furthermore, the official 5-day precipitation forecasts issued by the Extended Forecast Branch had an average skill score of 12.4 during this period.

Thus it appears that, although their prognostic 5-day mean 700-mb. charts are not accurate enough to give good specifications of precipitation by the method developed in this paper, the forecasters are making good use of other tools in predicting precipitation. In order to capture some of these factors and develop an operationally useful prediction scheme, attempts have been made to include various time lags and other predictors such as sea level pressure, 850-mb. moisture, present weather, and daily baroclinic height forecasts [9]. Additional work is in progress to incorporate more complex variables such as vorticity, vorticity advection, wind shear, lapse rate, and vertical velocity. Eventually it is hoped that a completely objective and reasonably accurate system of forecasting 5-day precipitation will be developed for routine application.

ACKNOWLEDGMENT

The author's principal assistant throughout the course of this project was Mr. Curtis W. Crockett. Other members of the Extended Forecast Branch of the U.S. Weather Bureau for whose assistance the author is sincerely grateful include the following: J. F. Andrews, R. A. Green, R. H. Gelhard, B. M. Lewis, R. K. Swiger, C. R. McGuire, and M. M. Wagner.

REFERENCES

1. G. W. Brier, "Revised Limits for Five-Day Total Precipitation Forecasts," U.S. Weather Bureau, Washington, D.C., 1946, 14 pp.
2. P. F. Clapp, "Further Empirical Studies of Wave Motion in the Westerlies," Unpublished report of Extended Forecast Branch, U.S. Weather Bureau, 1948, 18 pp.
3. D. C. Friedman, "Specification of Temperature and Precipitation in Terms of Circulation Patterns," *Journal of Meteorology*, vol. 12, no. 5, Oct. 1955, pp. 428–435.
4. D. L. Gilman, "Empirical Orthogonal Functions Applied to Thirty Day Forecasting," *Scientific Report* no. 1, Contract No. AF19(604)-1283, Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Mass., 1957, 129 pp.
5. D. L. Gilman, "A Test of the Forecaster's Skill at Specifying Weather from Circulation," Paper presented at 184th National Meeting of the American Meteorological Society at Washington, D.C., May 1960. (Abstract in *Bulletin of the American Meteorological Society*, vol. 41, No. 4, Apr. 1960, p. 191.)
6. H. F. Hawkins, Jr. "The Weather and Circulation of October 1956—Including a Discussion of the Relationship of Mean 700-mb. Height Anomalies to Sea Level Flow," *Monthly Weather Review*, vol. 84, no. 10, Oct. 1956, pp. 363–370.
7. W. H. Klein, "Winter Precipitation as Related to the 700-mb. Circulation," *Bulletin of the American Meteorological Society*, vol. 29, no. 9, Nov. 1948, pp. 439–453.
8. W. H. Klein, "A Hemispheric Study of Daily Pressure Variability at Sea Level and Aloft," *Journal of Meteorology*, vol. 8, no. 5, Oct. 1951, pp. 332–346.
9. W. H. Klein, "Five-Day Precipitation Patterns Derived from Circulation and Moisture," Paper presented at the International Symposium on Humidity and Moisture, May 22, 1963, Washington, D.C. (Proceedings to be published in 3 volumes by Reinhold Publishing Co., New York, N.Y., in 1964.)
10. W. H. Klein, B. M. Lewis, and I. Enger, "Objective Prediction of Five-Day Mean Temperatures during Winter," *Journal of Meteorology*, vol. 16, No. 6, Dec. 1959, pp. 672–682.
11. F. Lewis, "Multiple Regression Program BCD Input," Detachment 2, Hq. Air Weather Service, Electronic Computer Branch, Suitland, Md. 1962, (unpublished).
12. H. A. Lintner, "Objective Specification of Five-Day Mean Weather from Five-Day Mean Circulation Patterns," Part 4 of *Studies in Synoptic Climatology*, Final report of Synoptic Climatology Project, Contract N5 ori-07883 Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Mass., 1956, pp. 123–130.
13. E. N. Lorenz, "Empirical Orthogonal Functions and Statistical Weather Prediction," *Scientific Report* No. 1, Statistical Forecasting Project, Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Mass., 1956, 49 pp.
14. T. F. Malone et al., *Studies in Synoptic Climatology*, (W. D. Sellers, ed), Final report of Synoptic Climatology Project, contract N5 ori-07883, Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Mass., 1956, 215 pp.
15. D. E. Martin and H. F. Hawkins, Jr., "Forecasting the Weather: The Relationship of Temperature and Precipitation over the United States to the Circulation Aloft," *Weatherwise*, vol. 3, nos. 4–6, 1950, pp. 89–92, 113–116, 138–141.
16. J. E. McDonald, "Remarks on Correlation Methods in Geophysics," *Tellus*, vol. 12, no. 2, May 1960, pp. 176–183.
17. J. E. Miller, "Studies of Large Scale Vertical Motions in the Atmosphere," *Meteorological Papers*, New York University, vol. 1, no. 1, 1948, 49 pp.
18. R. G. Miller, "The Screening Procedure," Part II of "Studies in Statistical Weather Prediction," Final report, contract no. AF19(604)-1590 Travelers Weather Research Center, Hartford, Conn., 1958, pp. 86–136.
19. J. Namias, *Extended Forecasting by Mean Circulation Methods*. U.S. Weather Bureau, Washington, D.C., 1947, 89 pp.
20. H. A. Panofsky, and G. W. Brier, *Some Applications of Statistics to Meteorology*, College of Mineral Industries, Pennsylvania State University, University Park, Pa. 1958, 224 pp.
21. K. E. Smith, "Five-Day Precipitation Patterns in the United States in Relation to Surface and Upper Air Mean Charts," Massachusetts Institute of Technology, Cambridge, Mass., 1942, 114 pp. (unpublished Masters Thesis).
22. C. K. Stidd, "The Use of Correlation Fields in Relating Precipitation to Circulation," *Journal of Meteorology*, vol. 11, no. 3, June 1954, pp. 202–213.
23. U.S. Weather Bureau, "Normal Weather Charts for the Northern Hemisphere," *Technical Paper* No. 21, Washington, D.C., 1952, 74 pp.
24. H. Wexler and J. Namias, "Mean Monthly Isentropic Charts and Their Relation to Departures of Summer Rainfall," *Transactions of the American Geophysical Union*, vol. 19, No. 1, Jan. 1938, pp. 164–170.